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# Interactive 3D Digital Models for Anatomy and Medical Education

Caroline Erolin

**Abstract** This chapter explores the creation and use of interactive, three-dimensional (3D), digital models for anatomy and medical education. Firstly, it looks back over the history and development of virtual 3D anatomy resources before outlining some of the current means of their creation; including photogrammetry, CT and surface scanning, and digital modelling, outlining advantages and disadvantages for each. Various means of distribution are explored, including; virtual learning environments, websites, interactive PDF's, virtual and augmented reality, bespoke applications, and 3D printing, with a particular focus on the level of interactivity each method offers. Finally, and perhaps most importantly, the use of such models for education is discussed. Questions addressed include; How can such models best be used to enhance student learning? How can they be used in the classroom? How can they be used for self-directed study? As well as exploring if they could one day replace human specimens, and how they complement the rise of online and e-learning.

**Keywords:** Three-dimensional (3D) anatomy, Interactive models, E-learning, Medical education, medical art and visualisation

## 1 Background

Anatomy is an inherently three-dimensional (3D) subject and learning the 3D relationships of structures is of the utmost importance. Research has shown that 3D digital models can be a valuable addition to existing teaching methods in medicine and anatomy (Trelease 2016). Chariker *et al* (2012) found this to be especially true for more complicated anatomical structures. Research also indicates that achievement in several medical professions can be related to an individual's spatial ability (Anastakis *et al*, 2000; Hegarty *et al.*, 2009; Keehner *et al.*, 2004; Langlois *et al.*, 2014). Marks

(2000) claims that a poor understanding of 3D anatomy at undergraduate level compromises the training of postgraduates when they come to use 3D clinical imaging technologies.

In addition, models that are interactive and allow user control, have been found to be particularly helpful (Nicholson *et al.*, 2006; Stull *et al.*, 2009; Estevez *et al.*, 2010; Meijer and van den Broek, 2010; Tam *et al.*, 2010). Research by Stull *et al* (2009) suggested that students with active control over a 3D object, compared with passive observation (i.e. kinaesthetic and visual learning as opposed to visual alone) were better able to identify anatomical features from a variety of orientations.

## **1.1 A Brief History of Virtual 3D Anatomy Resources**

The value of viewing anatomy in 3D has been appreciated for some time. Long before modern digital models were developed, wax and more recently plastic models of anatomical structures have been used in medical education alongside cadaveric specimens and two-dimensional (2D) illustrations. In addition, techniques have been developed to allow depth perception of otherwise 2D illustrations and photographs. The technique of stereoscopy (which creates 3D depth perception by simultaneously showing two slightly different views of a scene to the left and right eye) dates back to the mid-19th century when 'stereoscopes' were used in medical education to depict anatomy and medical conditions. The appearance of most stereoscopes was not unlike the 'View-Master' toys of the 1980's and 90's, and indeed also bore more than a passing resemblance to modern virtual and augmented reality headsets. Doctors published 'stereo-cards' which depicted anatomical structures, diseases and even surgical procedures. Such devices appear to have fallen out of use sometime after the 1920's however, perhaps due to the rise of other technologies, and the increasing availability of cadavers.

Throughout the 20th Century, various technologies have been developed which have allowed researchers and clinicians, as well as medical artists/illustrators to create digital 3D models. Computerised Tomography (CT) and Magnetic Resonance Imaging (MRI) were developed in the 1970's and had an enormous impact on the diagnosis of

and treatment of numerous conditions. In addition, they could be reconstructed into 3D volumes which could be used for educational and research purposes.

The National Library of Medicine's Visible Human Project (VHP) ([https://www.nlm.nih.gov/research/visible/visible\\_human.html](https://www.nlm.nih.gov/research/visible/visible_human.html)) aimed to create detailed datasets of the normal male and female human bodies consisting of transverse CT, MRI and anatomical images from cryosection. Planning for the VHP began in 1989 with the male data set being completed in November 1994 and the female in November 1995. The long-term goal of the VHP is to connect image based anatomic data (models, software applications, cross sectional viewers etc) with text-based data in one unified resource of health information for healthcare professionals, students, and lay people (Jastrow and Vollrath 2003). Visible human projects have also been undertaken in China and Korea (Park et al. 2006) with the results also being made available to researchers.

In addition, the final decade of the 20th century saw a rapid development in 3D software, enabling artists to create digital models from scratch. 3D Studio Max was released to the public in 1990 with Maya following in 1998. Over the subsequent 20 years there has been a proliferation of such software which has developed considerably over just a few decades to allow artists to create and animate highly complex models.

Running concurrently to these developments has been the growth of online and e-learning. Today, there are numerous resources available including virtual learning environments, websites and applications for PC, Mac and mobile devices that contain interactive 3D models of human anatomy, which can be used both in the classroom as well as for self-directed study (Attardi and Rogers; 2015, Chakraborty and Cooperstein, 2018).

## **2 Creating Virtual 3D Interactive Models**

There are several means of creating your own 3D models. These can broadly be split into two categories; working with scanned data and creating models from scratch using a variety of 3D modelling software. There is considerable overlap between the two

however, and it is common practice to combine multiple approaches in a single project. For example, you may use CT data to reconstruct the basic geometry of a structure and then refine this and add colour using a 3D modelling package.

Below are outlined some of the most commonly used approaches to creating 3D models, highlighting the advantages and disadvantages of each.

## **2.1 Surface Scanning**

There are a wide range of surface scanners commercially available ranging greatly in quality and price (from a few hundred pounds to several thousand). Hand-held scanners tend to be more versatile than fixed and desktop scanners. However, it must be remembered that they are not usually wireless and still need to be connected to a computer and power source. There are exceptions however, with some scanners including batteries and onboard processors. Most hand-held and desktop surface scanners used in this field are based on either laser or structured light technology. Laser scanners typically create 3D images through a process called trigonometric triangulation. A laser is shone on the object and its reflection caught by one or more sensors (typically cameras), which record the changing shape and distance of the laser line as it moves along the object. The distance of the sensors from the laser's source is known, and as such accurate measurements can be made by calculating the reflection angle of the laser light.

Advantages of laser scanners include that they are generally very fast, usually highly portable, and are less sensitive to changing and ambient light (than structured light scanners). Disadvantages include that not all lasers are 'eye safe' when scanning living subjects, and they are usually less accurate than structured light scanners.

Structured light scanners work by projecting a known pattern onto an object and taking a sequence of images. The deformation of the pattern is measured to determine the objects shape and dimensions. Advantages of structured light scanners include that they are highly accurate, generally very fast, 'eye safe', and usually highly portable. The main disadvantage of structured light scanners is that they can be sensitive to changing and ambient light.

In addition, if either type of scanner uses colour camera(s), rather than black and white, they will be capable of capturing colour information in addition to shape. Whether this is important or not will depend on what is being scanned and for what purpose. However, in the fields of anatomy and medical education, such information is usually very useful.

Many scanners (of all types) can also encounter difficulties with certain types of surfaces which interfere with the scanning process. These include dark, transparent, mirrored and shiny surfaces, as well as hair and fur. Dark surfaces absorb the light, clear surfaces let the light through, and mirrored and shiny surfaces (as well as hair and fur) scatter and bounce the light in uncontrollable directions. There are some things that can be done to help when scanning such surfaces however, such as adapting the scanners settings, (particularly the sensitivity) as well as adapting the scanning environment by trying alternative lighting etc. If all else fails objects can be sprayed with a matte opaque coating to cover the problem areas. However, when scanning anatomical specimens this is often not an option, and other methods such as photogrammetry, various medical imaging techniques, or digital modelling should be considered.

When making a scan, the user should endeavour not to move the scanner or object too fast, as this can create errors or cause the scanner to lose tracking. Turntables can be a useful tool for ensuring a smooth movement and accessing all sides of an object. In many cases it may also be necessary to turn the scanned object over to access the underside. In these cases, the scanner software will usually be able to align multiple scans (either automatically if there is sufficient overlap, or manually) allowing the full 3D form to be captured.

## **2.2 *Photogrammetry***

Photogrammetry offers an affordable and accessible means of creating 3D models. Several 2D photographs of a static object are taken from different viewpoints allowing for measurements between corresponding points to be taken, thus enabling a 3D reconstruction of the object to be created. While large multi-camera systems allow for instantaneous image capture using hundreds of photographs taken from different

angles, such elaborate systems are not essential. In fact, a major advantage of photogrammetry is that it can be a relatively low cost means of 3D capture. While the quality of the camera equipment can affect the process and resulting model, it is certainly possible to get very good results with low cost cameras and even camera phones (a minimum resolution of 5 megapixels is a good starting point). Likewise, there are numerous photogrammetry software applications available, ranging in price from being completely free to costing several thousands of pounds. Good results can be achieved without spending too much however.

Photogrammetry is very sensitive to the resolution of the photographs used, with higher resolution images resulting in better models. Where good quality, sharp photographs are used however, the resulting texture map is often of a higher quality than that achieved with expensive surface scanners. Photogrammetry can be a highly accurate technique when carried out correctly. De Benedictis *et al* (2018) used photogrammetry to support the 3D exploration and quantitative analysis of cerebral white matter connectivity. The geometric resolution necessary to accurately reproduce the fine details required was estimated to be higher than 0.1 mm. Close-up photogrammetry acquisition was therefore undertaken to meet this specification.

As with surface scanning it is best to avoid surfaces that are shiny, mirrored or transparent as this can confuse the software used to reconstruct the 3D model. Photogrammetry software can also struggle with flat or featureless objects, as well as with objects containing holes and undercuts. The main disadvantage of photogrammetry however, is that a powerful computer is often necessary to process the large numbers of photographs taken.

When taking images for photogrammetry, it is best to do so in even lighting with a typical focal length of 35-50mm (maintaining a fixed focal length and distance from the object is ideal). It is generally best to avoid using extreme wide-angle lenses due to the inherent distortion they cause. A tripod, remote shutter control and turntable can also be useful additions to the kit. Ensure the camera is set to a high resolution and if using your phone's camera use the high dynamic range (HDR) setting where possible. Take photographs all around the object at different heights, aiming for each image to





## 2.3 CT and Medical Imaging

Various medical imaging modalities can be used to create 3D anatomical models. The most commonly used being CT (Computer Tomography), and MR (Magnetic Resonance) imaging. Both CT and MRI scans are typically stored using the DICOM (Digital Imaging and Communications in Medicine) format, which is the international standard to transmit, store, retrieve, print, process, and display medical imaging information<sup>1</sup>. There are a number of applications capable of viewing and manipulating DICOM files, ranging in price from being free to costing several thousands of pounds. Some applications are limited to just viewing the data, while others, (especially the costlier programmes) allow for more detailed processing and analysis.

It is usually necessary to 'segment' DICOM data (to determine the exact surface location of an organ/tissue structure), something that most DICOM viewers are capable of to varying degrees. Segmentation can be either manual or automated. There are problems with each approach; complete automatic segmentation is not possible for anything but large, easily differentiated organs and structures, whereas manually outlining structures on each cross-section is very time consuming and observer-dependent. Many researchers therefore use a combination of approaches. For example, Schiemann *et al* (2000) used a semi-automated method of segmentation for large structures and manual segmentation for smaller, more detailed areas. In addition, some of the smallest details such as nerves and blood vessels frequently require modelling freehand (Pommert *et al.*, 2000).

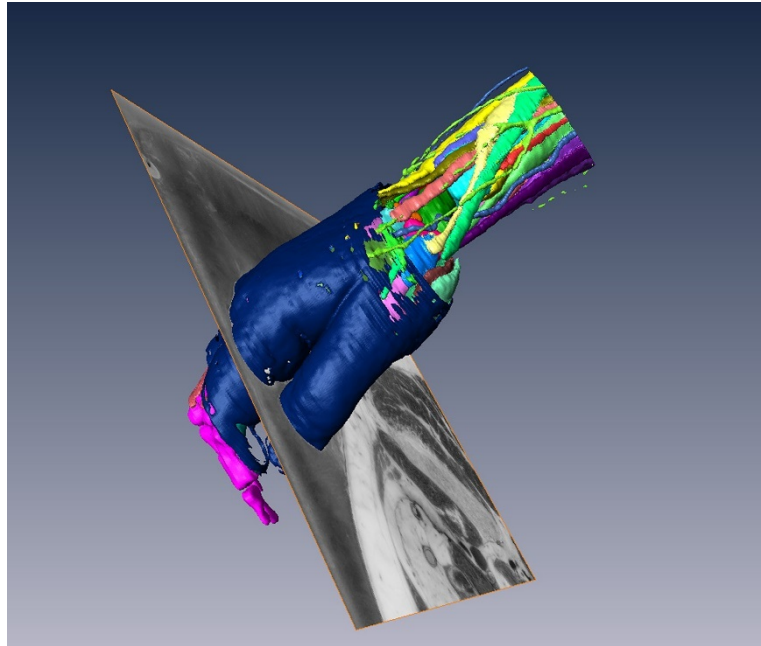
Once segmented, an isosurface can be created. An isosurface is a 3D equivalent of an isoline, representing points of a constant value, such as a particular density in a CT scan. The isosurface can usually be exported from the DICOM viewing software as either an STL or OBJ, both of which are standard file formats when working in 3D modelling and can easily be opened in most 3D applications.

Micro-CT scanners can also be used to create scans of smaller objects using much the same technology as clinical CT scans, but on a smaller scale with a greatly increased resolution. To generate a 3D volume, hundreds of angular views are

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<sup>1</sup> <https://www.dicomstandard.org/>

**Fig. 2.** Screenshot by the author from DICOM viewer and analysis software *Amira*, demonstrating several isosurfaces created using cryosection slices from the *Visible Human Project* female data set



captured while the specimen is rotated through 360°. These images are then reconstructed using software such as *VGStudio Max* to generate 3D volumetric representations of the specimens which can be exported as STL and OBJ formats as above.

In addition to CT and MRI, photographs of cryosections are sometimes used to reconstruct 3D models. Allen *et al* (2015) and Erolin *et al* (2016) both used images of cryosection slices from the VHP female data set, reconstructed in *Amira* as the basis of interactive 3D models (figure 2).

Advantages of using the medical imaging modalities outlined here include that they are able to capture internal as well as external features and are usually highly accurate, providing a 3D template that can be further refined using a variety of 3D modelling software. Disadvantages are that manual segmentation can be time consuming, and even then, (with the exception of micro-CT scans) small structures may not always be clear.

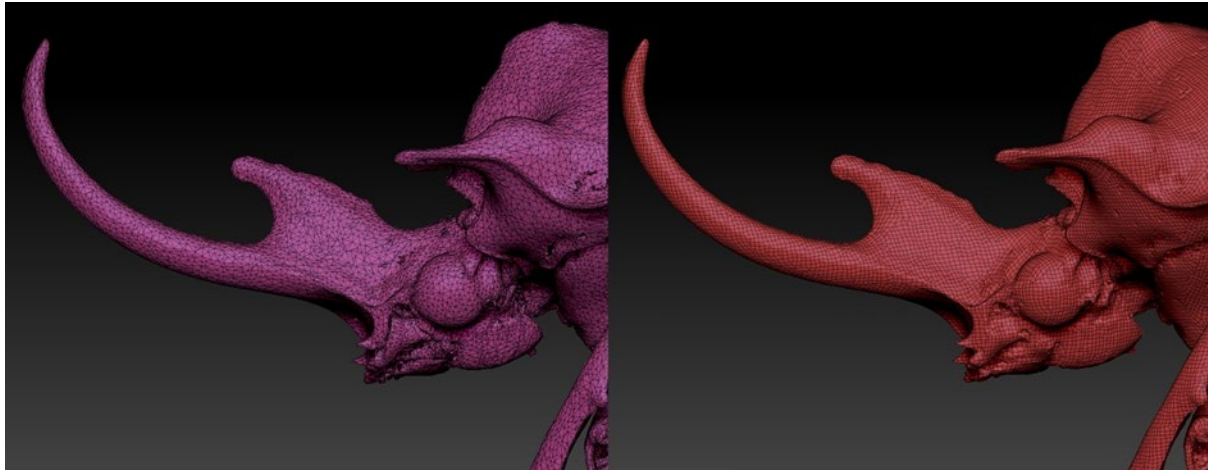
## **2.4 Digital Modelling**

The final means of generating 3D models to be discussed in this chapter is using 3D modelling software to create a model from scratch. Since the development of 3D

Studio Max and Maya in the 1990's the number of available applications has exploded, and the marketplace now contains a multitude of options. As with all the above, there is considerable range in quality and price, with applications being available for both PC and Mac systems as well as for mobile devices and even virtual reality (VR) headsets. Some applications have more limited functionality, specialising perhaps in modelling (ZBrush), or rendering and animating (KeyShot), while others are more all-encompassing (examples include 3D Studio Max, Maya, Cinema 4D and Blender).

There are also a wide range of modelling processes that can be employed, such as 'box modelling' and 'digital sculpting'. Box modelling starts with a primitive object (such as a cube) to which more can be added and modified by extruding, scaling, or rotating their faces and edges. In comparison, digital sculpting allows the user to interact with the model more as they would with physical clay, by pulling and pushing the surface to create the desired shape. The main advantage of box modelling is that the user has a great deal of control over the topology, meaning they can manage and predict how it will act if animated. Digital sculpting tends to be more intuitive (since it closely reflects physical sculpting) and allows for a higher level of detail to more easily be achieved. Many artists employ both methods, for examples using box modelling to create the basic shape and sculpting to add details. When creating 3D models for interactive anatomy and medical education, animation is not typically required, meaning that either of the above processes would be suitable.

Once the modelling stage is complete, it is frequently necessary to 'retopologise' the mesh (particularly when using digital sculpting). This recreates the surface with a more optimal geometry. It creates a clean, quad based mesh that is better for animation and texturing (adding colour). Retopology tools can also enable the polycount to be significantly reduced, which is important when creating interactive models (figure 3). Regardless of how they are disseminated, interactive 3D models must process the actions of a user and output them in 'real time', or at least close enough that the user cannot sense any delay. The more vertices/polygons a model has, the more computational power is required to ensure a fast render time, it is therefore important to ensure that such models are 'low poly' (Webster 2017). While there are no absolute limits to polygon counts, Blackman (2011) states that Unity (a video game development company) recommended a 30–40,000 vertex count (translating to



**Fig. 3.** Screenshot by the author from 3D modelling software ZBrush, showing a microCT scan of a Rhinoceros Beetle before and after being retopologised using the Dynamesh feature within ZBrush. This process recreates the surface with a more optimal geometry that can also be set to a lower polycount

approximately 60,000–80,000 polygons) for the fourth generation iPad, while newer devices are only getting more robust.

There are various means of adding colour to 3D models, but typically a texture and UV map will be required. UV mapping is the process of projecting a 2D image (i.e. the texture map) onto a 3D object. The letters "U" and "V" represent the axes of the 2D texture map since "X", "Y" and "Z" are already used for the axes of the 3D object in space. Most 3D modelling applications will be able to produce such maps relatively easily. In addition, there are a range of other maps that can be worth creating such as bump, normal and displacement maps. Bump and normal maps change how the light is calculated on the surface of a 3D model giving the allusion of additional detail, whereas displacement maps change the geometry itself.

Models imported from many surface scanning and photogrammetry software will already have UV and texture maps created. CT and MRI scans can be more problematic however. As these processes do not capture colour, texture and UV maps will not automatically be produced, and they can be difficult to create. This is because CT and MRI scans capture internal as well as external features, frequently creating models with large and highly complex surface areas that are difficult to unwrap.

It is possible to add colour without texture and UV maps however. Many applications allow for colour to be painted directly onto the model's surface, such as the Polypaint feature in ZBrush. This can be exported with an OBJ of the model, as what is known

as 'vertex colour'. It should be noted that vertex colours do not form part of the official OBJ file specification, however, some applications use an extended format and have added RGB information along with the vertex coordinates. A potential disadvantage of vertex colour however, is that in order for the colour textures to look sharp, the polycount of the models often has to stay higher than would be the case with a texture map.

It can also be beneficial to import scans (including surface, photogrammetry, CT and MRI) into a 3D modelling application to both refine the geometry (for example, by deleting unnecessary data and artefacts and repairing and remodelling any missing elements) and to add colour. Even where scans come complete with UV and texture maps, it can occasionally be beneficial to convert the existing texture map to Polypaint (in ZBrush) to correct for things such as harsh shadows captured during scanning.

There are many advantages to using 3D modelling software, both to create models as well as to refine scans. It is possible to generate 'clean' topologies, create a variety of useful maps and have a greater control over the final polycount. However, such software can be complex and time consuming to learn, with operator skill and experience being central to the quality and accuracy of the models produced.

### **3 Distribution**

There are various means of distributing interactive 3D models, and often projects will be distributed via several means. For example, the 3D models of spine procedures created by Cramer *et al* (Cramer et al. 2017) were published in Apple iBooks and online via Sketchfab, as well as being physically printed.

Below are outlined some of the common means of distributing 3D models, highlighting the advantages and disadvantages of each.

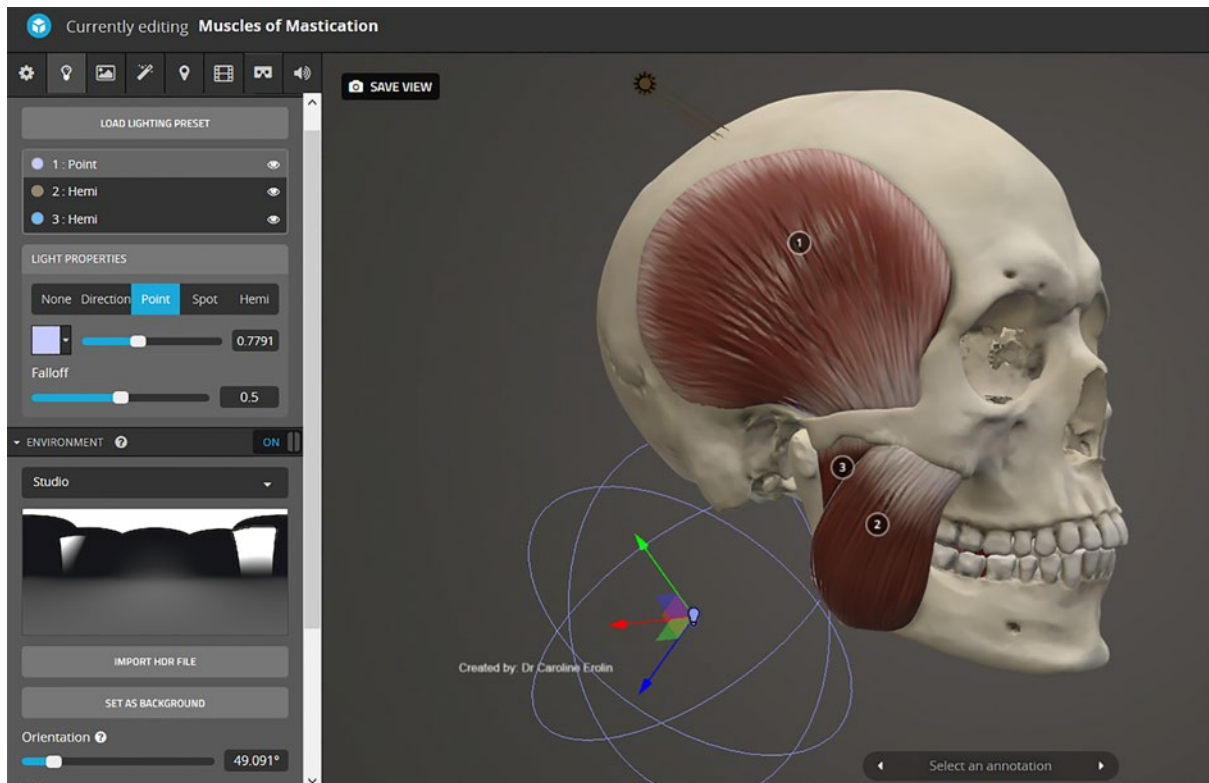


Fig. 4. Screenshot by the author demonstrating Sketchfab's 3D settings editor

### 3.1 Online

Interactive 3D models can be shared online, both on public webpages as well as being embedded in virtual learning environments and online courses. Today there are numerous platforms available for sharing 3D models online such as Sketchfab, and more recently Google's Poly and Microsoft's Remix 3D. Sketchfab was launched in 2012 and as such was of the first to platforms to enable 3D artists to easily share their work online. Since this time, it has grown to become the largest platform for immersive and interactive 3D, hosting over three million models as of 2018 (<https://sketchfab.com/about>). Sketchfab supports over 50 3D formats and is also capable of loading vertex colours and play 3D animations. Once uploaded numerous 3D properties of the scene and model can be adjusted including camera options, material properties and lighting (figure 4). Annotations and audio can also be added. Users can choose to make their 3D models private or publicly available with download options utilising Creative Commons licenses. As well as being available on the Sketchfab website and mobile apps, the 3D viewer can also be embedded on external

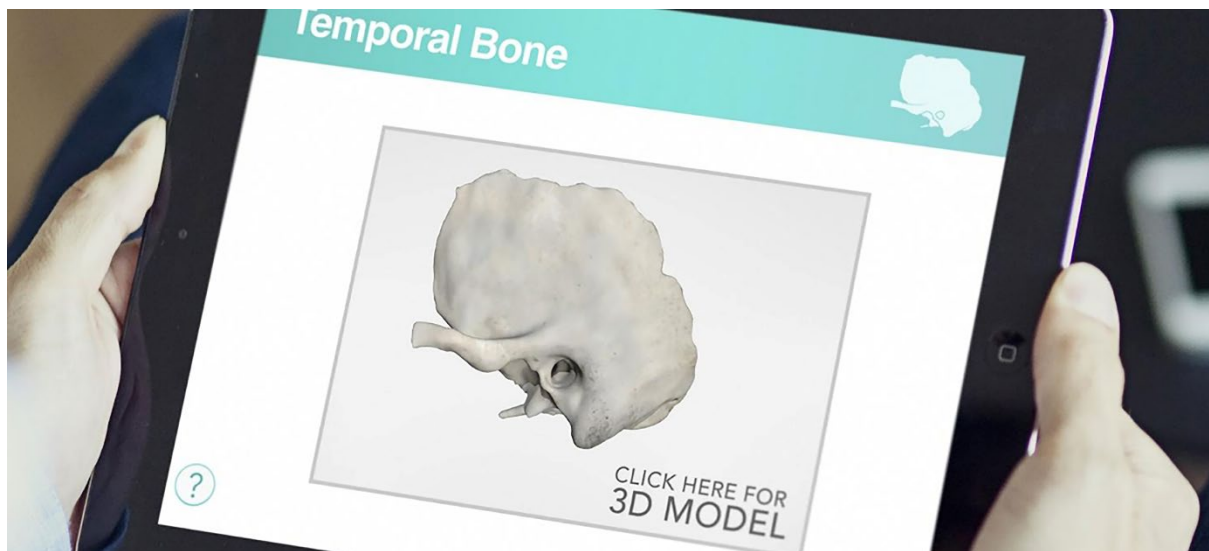
websites including many e-learning platforms (such as Blackboard and Moodle), making it ideal for use in education.

### **3.2 *eBooks and iBooks***

Electronic or e-books are another great way to share 3D models. eBooks come in a range of formats including MOBI, EPUB and iBook. It is worth considering which platform/device is most appropriate to the target audience before choosing which format to publish in. eBooks can be created in a range of software such as Adobe InDesign (although this does not currently support 3D) or using dedicated authoring applications such as Kotobee and Apple iBooks author.

The Apple iBooks store in particular, hosts a wide range of publications featuring interactive 3D anatomical models. This is probably due to the relative ease of embedding 3D models in iBooks, by simply using the '3D widget' to add your model of choice. Only models saved as COLLADA files (with the extension .dae) can be imported however, so it is important to export out this file type in advance. It is not currently possible to annotate 3D models in iBooks, so alternative means of identifying structures (such as using supporting illustrations) need to be considered. It should also be noted that if numerous or complex models are added to a single iBook, the file can become very large and have difficulty loading. However, it is possible to embed HTML code and therefore online models (such as those on Sketchfab) within iBooks, enabling larger models to be displayed. Although it must be remembered that an internet connection is required for them to load (McDougal and Veldhuizen 2017) (figure 5).

As well as the education of anatomy and medical students, iBooks can be used to inform the public about their conditions and potential surgery. Research by Briggs *et al* (2014) showed that patients presented with iBooks during their preoperative assessment found the resource to be very useful with the majority no longer feeling the need to seek further information from external sources.



**Fig. 5.** Image of iBook created by the Dundee Dental School, with embedded models from Sketchfab. Image courtesy of the School of Dentistry at the University of Dundee.

### 3.3 3D PDF

PDFs support the integration of interactive 3D models and are generally easy to create. They can provide a great way to share 3D models and can be viewed without the need for online access. They are particularly useful for creating interactive handouts and revision aids. It is important to note that only Universal 3D (U3D) files can be imported however. It is easy to create such files using software such as Adobe Photoshop where a more common 3D format such as OBJ or STL can be exported as U3D. Unfortunately, 3D PDFs are not supported by IOS devices at present.

To create a 3D PDF, you will need Adobe Acrobat Pro or DC. Under *Tools* and *Rich Media*, you will find the option to *Add 3D*. Drag a rectangle across the page to define the canvas and browse to select an appropriate file. The canvas can be moved and resized using the *Select Object* tool. Double clicking on the canvas with the *Select Object* tool will open the 3D properties dialogue box where various attributes such as lighting and rendering style can be altered. Annotations can be added by selecting *Add 3D Comment*, under the drop-down menu to the top left of the canvas. Annotation colour can be changed by going to *Preferences, measuring (3D)*, and changing the *3D Measuring Line Colour*.



### **3.4 Virtual and Augmented Reality**

The term 'Virtual Reality' (VR) as it is used here, refers to the interaction with an artificial object or environment through computer software or website, using an immersive head mounted display (HMD), such as the Oculus Rift and HTC Vive headsets (<https://www.oculus.com/en-us/> & <https://www.vive.com/uk/>) to create fully immersive experiences.

The term Augmented Reality (AR) covers a broader range of applications, including the use of QR codes and image triggers to launch additional information such as 3D objects on mobile devices as well as the use of HMDs such as the Microsoft HoloLens (<https://www.microsoft.com/en-IE/hololens>). AR HMDs differ from those used for VR in that they allow the user to see the virtual object superimposed over the real world. This can have certain benefits such as enabling the user to still see and communicate with those around them as well as ensuring they don't trip over furniture or walk into walls.

Moro *et al* (2017) investigated the use of VR and AR for students learning structural anatomy and found them to be as effective as commonly used tablet-based applications. In addition, they both provided additional benefits such as increased student engagement, interactivity and enjoyment. There were some adverse effects noted however such as mild nausea, blurred vision and disorientation, particularly with VR.

Your own models can be viewed in both VR and AR using 'off the shelf' solutions such as Sketchfab, requiring no additional software or programming skills. Sketchfab features a VR editor where the scale, viewing position and floor level can be set for each model, in preparation for viewing with a VR device (figure 6). The mobile application can also be used to view models in AR on mobile devices, leveraging Apples' ARKit for iOS and ARCore on Android.

As discussed below, bespoke applications are another way to integrate 3D models into a more complete VR or AR learning package, where the principles of gamification (the use of game design elements to increase user engagement) can more readily be employed.

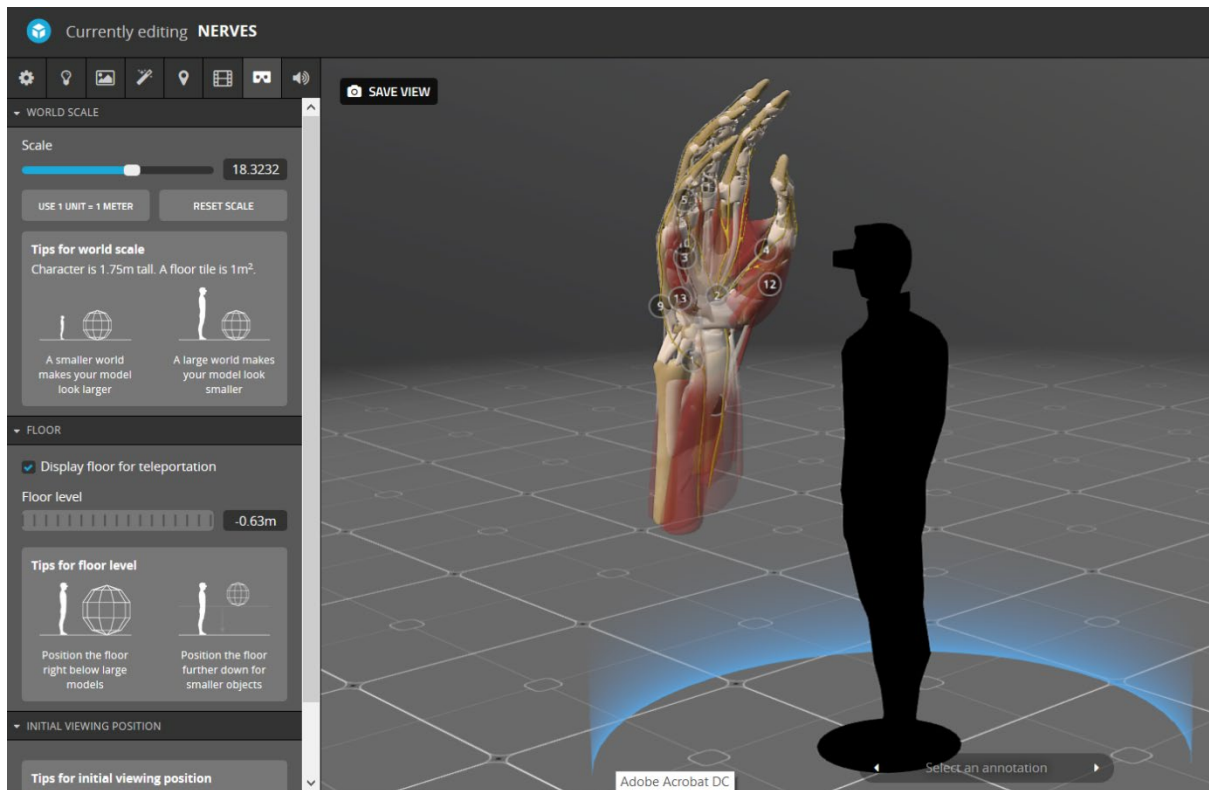


Fig. 6. Screenshot by the author demonstrating the VR options within Sketchfab's 3D settings editor

### 3.5 *Bespoke Applications*

Bespoke applications offer one of the most comprehensive means of distributing interactive 3D models as they can be combined with additional content in a highly engaging manner. Such applications are typically created using the game development platforms Unity and Unreal. Using such platforms, it is possible to create a wide range of applications, such as medical and surgical simulators and 'serious games' (Gorbanev et al. 2018). Such applications can be created for PC, Mac and both IOS and Android mobile devices.

Creating bespoke applications is usually more complex than the other distribution methods described and may often be best tackled through a team approach, involving medical artists, programmers and anatomists/medics working together. Applications which utilise 3D interactive models may take several forms and use a variety of supporting hardware such as mobile devices, haptic interfaces and VR/AR headsets.

Applications for both IOS and Android devices can be created using one of several 'app building' platforms now available, requiring no coding knowledge or experience, and distributed via their respective stores. In addition, Apples' ARKit for iOS devices and ARCore on Android can be used to create bespoke AR applications for use on mobile devices.

The addition of haptic feedback is certainly worth considering as it appears to increase student interest in the exploration of virtual objects. Jones *et al* found that students typically spent more time examining objects where there was haptic as well as visual feedback (2002). In a later study (Jones *et al* 2005) they found that students who used a haptic or haptic and visual interface to explore virtual objects, spent considerably more time exploring the 'back' of objects when compared to those using a visual interface only. This is particularly relevant to anatomy education, where both the anterior and posterior of structures are often of equal importance.

Bespoke VR and AR applications for use with HMDs can also be created using the Unity and Unreal platforms and allow for much more immersive experiences than applications viewed on 2D screens. In addition, they allow the user to view models in stereoscopic 3D due to each eye viewing a slightly different image. One of the main advantage of this is reported to be the depth cues generated from binocular vision (Henn et al. 2002). Depth cues such as convergence (only effective on short distances (less than 10 metres), when our eyes point slightly inwards) and binocular parallax (referring to the slightly different images seen by the left and right eyes) help in the understanding of the complex relationships between structures, which cannot be obtained through monocular vision alone (Henn *et al.*, 2002).

### **3.6 3D Printing**

Interactivity is not limited to on-screen digital media. 3D printing offers a means of creating physical models from digital files. Within anatomy and medicine, 3D printing is being used for a range of applications including education, surgical planning, surgical guides, implants and prosthetics (Cramer et al. 2017). 3D prints of real specimens can be created from CT and surface scans, allowing for fragile and rare specimens to be duplicated. Digital models created using 3D software can also be

printed, meaning the same model can be viewed on screen (or in VR/AR) and held in the hand simultaneously. This can allow for additional information to be communicated via annotations or audio on the digital model and ensures consistency between 3D prints used in the classroom and digital models used for self-directed learning.

3D prints can be made from just about any digital model so long as it is 'watertight', (i.e. there are no holes in the mesh) and there are no 'floating' parts (i.e. that all parts of the model are connected). Many 3D programs will have tools for checking that models are ready to print. For example, MeshLab (an open source system for processing and editing 3D triangular meshes) can be used to check that meshes are watertight. Simply import your model and from the drop-down menu for *render* select *show non manif edges*. Rotate the model and if the object is not watertight, the non-manifold edges will be highlighted.

A wide range of 3D printers are now available, utilising a variety of technologies ranging greatly in quality and price. 3D prints are most commonly produced in a hard plastic, but other materials such as soft/flexible plastics are available. Some printers even have multiple nozzles allowing for different materials to be printed simultaneously. There is a good selection for under £5000 making them readily accessible for universities and individuals. In addition, there are several companies who will produce 3D prints from digital files emailed to them. An advantage of using a company to produce prints is that they often have access to higher quality printers and can also undertake any further processing of the print (such as removing support structures) for you.

## **4 Using Interactive 3D models for Anatomy and Medical Education**

3D interactive models can be used to support and enhance anatomical and medical education both in the classroom as well as through self-directed study online. Many of the methods for distributing models outlined above can be used within both contexts. Indeed, ensuring that there is consistency between what is viewed in the classroom and externally is one of the benefits of creating bespoke models.

## **4.1 *In the Classroom***

Interactive 3D models can be used by educators when giving presentations, either during traditional 'face to face' lectures or during workshops. Although it is not currently possible to embed interactive 3D models into PowerPoint presentations (3D models can be imported, but they do not retain their interactivity once in presentation mode), it is easy enough to link out to online models. This can be particularly useful for practical classes, for example, allowing the lecturer to highlight features while students are handling specimens.

Tablets have also been shown to be useful tools in workshops, with Chakraborty and Cooperstein (2018) demonstrating that instructors were able to successfully incorporate the iPads into laboratory sessions, with 78% of the students who used them feeling that it helped them to better learn the course material. Tablets can be used to view both bespoke eBooks/iBooks and applications as well as models hosted online. This can be particularly useful when used alongside real specimens to aid in the identification of structures, even linking these to clinical or surgical practice. AR can be also be integrated with tablets to further enhance the amount of additional information they can provide. For example, as well as QR codes many AR apps can be triggered by images and objects, allowing them to be linked to anatomical illustrations, models, and even plastinated specimens.

Bespoke applications can be tailored to a curriculum and depending on the system requirements can frequently be used equally well within a classroom setting and externally. 3D PDF's can also be used in lectures and practical classes in place of traditional printed handouts where computers are available. At the University of Dundee, the use of printed handouts and books in the dissection room has been replaced by a computer at each station to provide bespoke dissection guides.

As most students do not currently have access to high-end VR and AR HMD's at home, these are currently most likely to be utilised on campus. They can either be integrated into taught classes or provided for independent student use. There are several practical considerations around the use of such HMD's however, including health and safety (tripping over wires, walking into walls etc), side effects (such as nausea), and cost/resource issues, such as the need for high end computers and

physical spaces that are set up for their safe use. VR and AR can be particularly useful for subjects that are usually difficult to teach. They have been shown to provide increased interactivity and enjoyment (Moro et al. 2017) which can be useful for engaging students in complex topics. VR and AR technologies are moving at a fast pace with new headsets being realised annually. Newer headsets such as the Oculus Quest (due to be released early 2019) will utilise 'inside out' tracking, meaning the sensor/camera is placed on the device itself and looks out to determine its position in relation to the external environment (in comparison to the Oculus Rift and HTC Vive which use outside-in tracking where the headset is tracked by an external device), allowing for it to be used just about anywhere. In addition, the Quest will be an all in one device, with no need to be wired to a PC. Such advances will no doubt enable an easier integration of VR and AR to the classroom as well making wider adoption in the home more likely.

Finally, 3D prints can be used both in place of, and in conjunction with cadaveric and dry bone specimens. This may be to provide additional material, to allow handling of prints in place of particularly fragile specimens, or to help clarify what is being seen on the real specimen. Lim *et al* (2016) studied the use of 3D printed hearts in medical education. Participants (who were undergraduate medical students) were randomly assigned to one of three groups; cadaveric material only, 3D printed material only, or a combination of cadaveric and 3D printed materials. Post-test scores were significantly higher for the 3D printed material group compared to the others, suggesting that 3D prints can provide a suitable adjunct to the use of cadaveric material and may even have some benefits. One potential benefit of 3D prints is that structures often appear clearer than on the real specimen. In addition, undergraduate students faced with cadaveric material for the first time may also be more comfortable in handling and learning from 3D prints, which can in turn facilitate comfort levels with the eventual use of cadavers (Lim et al. 2016).

## **4.2 Self-directed Study**

Over recent years there has been a shift in medical education, and higher education in general, away from traditional didactic lectures and tutorials towards more self-directed and online education (Birt et al. 2018). This includes e-learning (which utilises electronic resources to deliver curricular content outside of a traditional classroom), blended learning (a combination of learning at a distance and on-campus) and even 'flipped classrooms' (where students are introduced to material ahead of class, usually at home and online, with in-class time being used to deepen understanding through the application of knowledge and further discussion).

Interactive 3D models that are available online are highly versatile. As well as being used in the classroom they are readily accessible anywhere there is an internet connection (although larger models may require higher connection speeds), and thus facilitate student learning both at home and while travelling. For example, the University Medical Center Groningen utilises Sketchfab to host models used in their e-learning modules, making them accessible not only to their own students but publicly under a creative commons attribution, non-commercial, share-alike license (<https://sketchfab.com/eLearningUMCG>).

Virtual learning environments and online modules can be used to create private, bespoke learning environments for specific groups of students. This can be useful for creating more in-depth resources and for sharing sensitive models, such as those based upon real human remains. For example, Allen *et al* (2015) developed an interactive 3D model of the anatomy of the eye to assist in teaching ocular anatomy and movements at both undergraduate and post graduate levels. The resulting learning module was made available both online and as an application that could be downloaded onto students' personal computers.

eBooks, iBooks, and 3D PDFs can also be used just as readily at home as they can in the classroom. Publishing the same material in a range of formats will help to ensure that most, if not all students can readily access the material for self-directed study and revision.

As discussed above, most students do not yet have access to high end VR and AR HMD's at home. However, mobile VR solutions such as Google Cardboard and

Daydream go some way towards bringing VR to the home environment and upcoming devices such as the Oculus Quest will likely further the adoption of VR by the public.

Finally, 3D prints, while typically used in a classroom setting can also be signed out and taken home by students, something that is clearly not possible with real anatomical specimens.

## **5 Conclusion**

Over the last several years, the time dedicated to teaching anatomy has been decreasing in both the UK and US (Leung et al. 2006; Pryde and Black 2006). This is likely a result of increasing student numbers as well as an increase in course content from areas such as molecular biology. Some medical schools have even stopped teaching dissection altogether, such as the Peninsula Medical School at the University of Exeter (McLachlan et al. 2004) and many universities are turning to digital resources to address some of their educational requirements.

However, many believe that dissection teaches skills which are either difficult or impossible to learn by other means, (Aziz, A. 2002; Rizzolo and Stewart 2006) such as:

- Exposure to death, and the development of a 'professional' attitude ('the first patient')
- Teamwork and communication skills
- 3D learning and spatial awareness
- Exposure to anatomical variability
- Encouraging differential diagnosis
- Manual dexterity

Some of the items on this list can likely be addressed by other teaching modalities and technologies, such as use of simulated patients and virtual ward environments to facilitate teamwork and communication, and 3D interactive models for teaching spatial awareness. Others however are more difficult to address. Exposure to death (in a



controlled environment and with support available) is not possible via other means and can help students in developing empathy and a 'detached concern' necessary for good practice (Aziz, A. 2002). The normal anatomical variability often seen in the dissection room is also not easily replicated in models (either traditional or virtual), but is something of particular importance to medicine, especially surgery, as well as other professions such as forensic anthropology.

Interactive digital models can be a useful addition to anatomy and medical education, both to impart some of the skills commonly attributed to traditional dissection teaching, as well as addressing concerns over costs and resources. However, rather than choosing between cadaveric dissection and new technologies, there may be more value in utilising such technologies to enhance existing teaching practices rather than replacing them (Aziz, A., 2002; Biasutto *et al.*, 2006; Rizzolo and Stewart, 2006).

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